The Results of Recent MICE Superconducting Spectrometer Solenoid Tests

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Abstract— **The MICE spectrometer solenoid magnets will be the first magnets to be installed within the MICE cooling channel. The MICE spectrometer solenoids may be the largest magnets that have been cooled using small two stage coolers. During the previous test of this magnet, the cooler first stage temperatures were too high. The causes of some of the extra first stage heat load has been identified and corrected. The rebuilt magnet had a single stage GM cooler in addition to the three pulse tube coolers. The added cooler reduces the temperature of the top of the HTS leads, the shield and of the first stage of the pulse tube coolers.**

***Index Terms*—Solenoid Magnet Tests and Pulse Tube Cooler**

I. Introduction

The MICE spectrometer solenoids must provide a uniform magnetic field for the five plane scintillating fiber trackers that are within the 400-mm diameter magnet warm bore[1]. The trackers are used to analyze the muon beam emittance change in the cooling channel.

The spectrometer solenoid vacuum vessel is 2735-mm long and 1404-mm in outside diameter [2]. On top of the round vacuum chamber is a service turret that contains the four coolers and the leads. The 2515-mm long cold mass consists of five superconducting coils. They are two 200-mm long match coils (M1 and M2) that match the muon beam from the absorber focus coil (AFC) module into the three-coil tracker section (E1, C, and E2) of the spectrometer magnet.

The tracker section of the magnet consists of two 110-mm long coils at the ends of a long solenoid that is 1314-mm long. The three coils will generate a uniform field (better than ±0.3 percent) over a length of 1000 mm and a diameter of 300 mm. The two match coils and the three coil tracker set are powered by three 300-A power supplies. The two 110 mm-long end coils are tuned using a pair of 60-A power supplies [3].

The magnet was designed to be cooled using three PT-415 pulse tube coolers that develop 42 W at 40 K on the 1st stage and 1.5 W at 4.2 K on the 2nd stage. Since the two magnets will be shipped long distances, drop-in coolers are used [4]. These coolers will be removed during shipment from the vendor to Fermilab in the USA and from Fermilab to the Rutherford Appleton Laboratory in the United Kingdom.

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II. Basic Design of the Spectrometer Magnets

The spectrometer magnets were wound with conductor with a Cu to Nb-Ti ratio of 4. The conductor has 222 filaments that are ~41-μm in diameter. The dimensions of the insulated conductor are 1.65 by 1.00 mm. The conductor nominal twist pitch is 19 mm. The conductor (from 4-billets) was delivered in six pieces that ranged in length from 11 km to 36 km.

The five coils (M1, M2, E1, C, and E2) were wound on a single forged 6061-T6-Al mandrel. None of the ten coils (both magnets) have splices within them. The cryostat consists of a liquid helium vessel, an 80 K thermal shield, cold mass supports designed for 500 kN (in the axial direction) and a stainless steel vacuum vessel. A schematic representation of the magnet (not drawn to scale) is shown in Fig. 1.

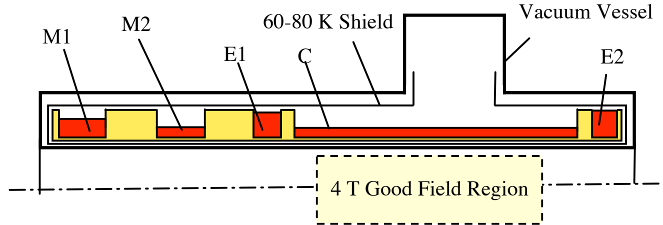

Fig.1 A Schematic Cross-section of the MICE Spectrometer Solenoid

The two magnets were completed a year apart. From the standpoint of the beam, the two spectrometer-magnets are identical [5] [6]. As a result of the 2009 test, magnet 2 was rebuilt with a single stage GM cooler (See Fig. 2), in order to reduce the temperature of the tops of the HTS leads [7].

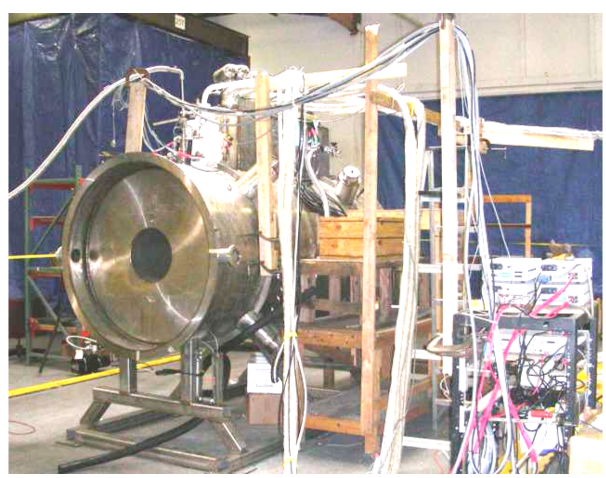

Fig.2. The Rebuilt Spectrometer Solenoid 2 with its Three PT-415 pulse Tube Coolers and AL-330 GM Cooler in Operation

Fig. 3 shows the circuits for the charging and quench protection for the two matching sections (M1 and M2) and three coil spectrometer section (E1, C, and E2). Each match coil and the three-coil spectrometer section are powered by a 300A at 10V power supply. The power supply circuits were modified to allow for a controlled discharge as well as a controlled charge from 0 to 300 A at voltages of ±6 V. In addition there is a rapid discharge system [8]. Current in coils E1 and E2 is adjusted using ±60 A at ±5 V power supplies.

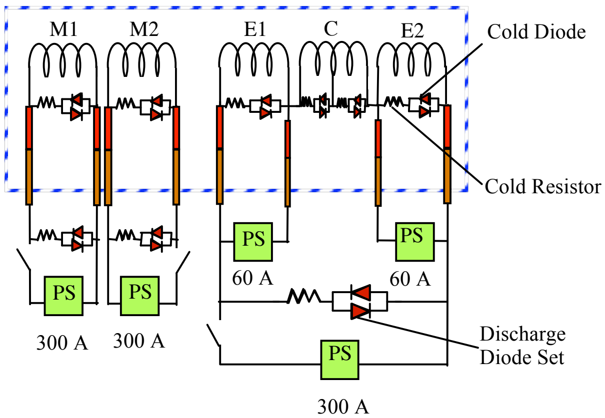

Fig.3. The Power Circuit and the Quench Protection Circuits for Each of the MICE spectrometer solenoids

The spectrometer magnet quench protection is passive. The two match coils each have back-to-back diodes and a resistor across them, which protect the coils in the event of a lead failure. The end coils E1 and E2 of the three-spectrometer coil set also have back-to-back diodes and resistors across them. The center (C) solenoid of the spectrometer solenoid set is sub-divided into two parts with back-to-back diodes and resistors across them. Thus the three-coil spectrometer section has four sub-divisions, which reduces the voltage to ground and protects the magnet three-coil tracker section [9]. The hot spot temperature in the long center coil is further reduced by quench back from the 6061-aluminum mandrel.

III. The Results of the Cooler and Lead Tests

The second magnet was cooled down the first time in the summer of 2009. During that test, the HTS lead furthest from the three two-stage coolers burned out. The heat leak into the magnet shield was too high. As a result, the temperatures on the first-stages of the three pulse tube coolers were also too high. The cause of the excessive heat leak into the first stage of magnet 2 (now called magnet 2A) is not well understood. It was determined that one of the causes of the excess heat leak to the first stages was that the copper leads from 300 K to the cooler first stages were improperly designed. It appeared that the IL/A for these leads was too high.

In order to test this hypothesis, a test of the leads and a single two-stage cooler was done using the same apparatus that was used for the previous cooler tests [4]. This apparatus consists of the cooler, the drop in sleeve, the helium tank, copper leads, HTS leads, and 4 K superconductor in the tank. This test permits one to test various lead designs in a system that mimics the copper leads, the HTS leads and a superconducting circuit with similar parameters as the magnet. The lead-cooler test apparatus is shown in Fig. 4.

Fig. 4. The Cooler and Lead Test Apparatus Top Plate. (Shown are the PT415 Cooler, the Tops of the Copper Leads and the Instrumentation System.)

During the cooler-lead test two different lead pairs were tested. The first lead pair with an IL/A = 5.2x 10^6 A m^{-1} was a pair of the leads used in Magnet 1 and magnet 2A. These leads were the same as leads used on a number of magnets built for LBNL during the last ten years. During the cooler lead test, we determined that the IL/A was too high. A second pair of leads with an IL/A = 3.3 x10^6 A m^{-1} was tested with the same apparatus [10]. A comparison of the heat leak into the cooler 1st stage for two lead pairs is shown in TABLE I.

TABLE I. Heat Flow per Pair for Two Lead IL/A's Tested in the Cooler-Lead Experiment

Lead	Lead IL/A (A m^{-1})	1^{st}-stage Heat Flow (W) I = 0 A	I = 275 A
1a	5.2 x 10^6	8	42
1b	3.3 x 10^6	16	31

TABLE I shows that the leads used in magnet 1 and magnet 2A (leads 1a) had an IL/A that was too large. This resulted in a low heat flow to the cooler at zero current. At the full design current the heat flow to the coolers at 275 A was too high. When one looks at the I^2R heating in the copper leads one finds that this heating is even higher. The tops of the leads 1a ran hot, with an additional 15 W per pair leaving the 300 K ends of the leads. The leads used in magnet 2B (leads 1b) are close to being optimum [11]. The tops of these leads run a little colder than they should at 275 A. The first-stage heating at the full design current for magnet 2A was about 80 W higher than for magnet 2B. This was later verified from the magnet test data in the test of magnet 2B [12].

IV. Changes in Magnet 2B

The copper leads from room temperature to the HTS leads were not the only problem that occurred in magnet 2A. With no current in the new leads (leads 1b), the net heat flow into the top of the HTS leads would be higher than the leads used in magnet 2A. This means that the temperature at the end of the copper plate farthest from the cooler would also be higher when there is no current in the leads. The problem of the excess heat into the cooler first stage was only partially solved, because the cold mass and cylindrical shield were not removed from the cryostat vacuum vessel. All of the changes in magnet 2B were made in the turret part of the magnet.

In order to provide extra cooling for the tops of the HTS leads and the extra heat flow coming from the shield, a single-stage Cryomech AL-330 GM cooler was added to cool the copper plate that the HTS leads are attached to. A GM cooler can be used on the spectrometer solenoid, because the magnetic field where the cooler is located is low <0.05 T [13]. The AL-330 cooler will cool to temperatures down to 10 K. The cooler can provide 185 W of cooling at 55 K on 60 Hz power. The single-stage cooler was installed at the end of the copper plate away from the pulse tube coolers. The copper plate that the HTS leads are attached to is now cooled from both ends. In addition, the copper plate was thickened to improve the heat transfer along the plate. The cooler installation is shown in Fig. 5.

Fig. 5. Installation of Two PT415 Cooler Drop-in Cans (left) and a Single AL-330 GM Cooler (right) on Magnet 2B. The leads will be installed on the copper plate between pulse tube coolers and the single-stage GM cooler. Note: There is a flexible connection between the copper plates and between the single-stage cooler cold head and the end of the copper plate.

V. THE RESULTS OF THE MAGNET 2B TEST

Magnet 2B was cooled down and tested in March of 2010. The magnet was cooled down using liquid nitrogen and liquid helium. The shield was pre-cooled using liquid nitrogen. Once the magnet was cold, the coolers were turned on. Once the shield was cooled down with the coolers, it became clear that no liquid nitrogen was needed. Using the AL-330 single-stage GM cooler resulted in copper plate temperatures at the ends of the HTS leads being reduced by 30 to 35 K, as compared to the previous test (magnet 2A). The single stage cooler removed about half of the heat load from the shield and the leads. The shield was about 20 K cooler than it was for magnet 2A. Even with 250 A in the leads, the cooler first-stage temperatures were less than 47 K.

The test included testing the new power supply control system that permits one to control the magnet current as it is going both up and down. The magnet went through a series of training quenches with all five coils connected in series. (See Fig. 6.) All of the magnet coils were trained to a current of 258 A, which is ~94 percent of the design current. After the quench, it was found that one of the low temperature leads to the M2 coil was broken. The lead break occurred in an LTS lead passing through the vacuum feed-through between the bottom of the HTS lead and the voltage tap connected to the magnet coil and the quench protection circuit across the coil.

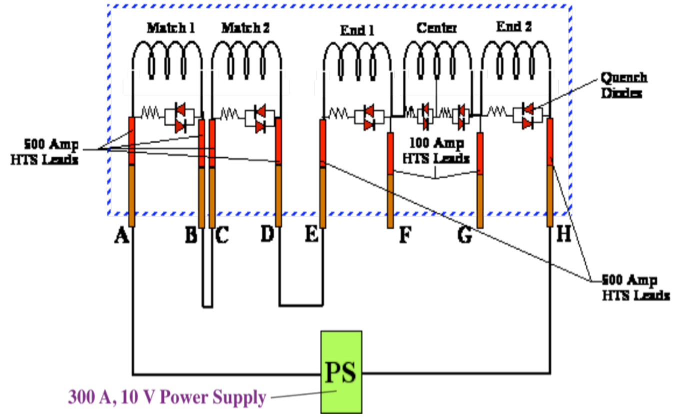

Fig. 6. The Circuit for Five Spectrometer Magnet Coils Connected in Series

After the magnet cold mass was removed from the vacuum vessel, it was determined that the coil M2 lead disconnect occurred within the liquid helium tank in a 0.8 mm diameter low copper to superconductor ratio wire that passes through the vacuum feed-through. It is not clear whether the lead break occurred, as a result of the quench or vice versa. A break in the circuit shown in Fig. 6 will cause the magnet to quench, because the diodes will fire and the magnet current will be diverted through the series diodes and resistors.

In March 2010, the M2 coil lead failure cause was not well understood. When the quench occurred, the cryostat was half full. The temperature in the gas space above coil E2 was about 5.2 K, due to AC losses in coil E2. In other less confined regions, the gas temperature was lower. In the LTS lead location magnetic field was <1.0 T. The superconductor critical temperature was >7.2 K. Increased temperature alone was not the cause the lead failure. There were two lead failure scenarios; 1) conductor motion due to magnetic forces, and 2) an added current pulse in coil M2 induced by a quench of the other coils in the magnet. These scenarios were investigated. Since the superconductor that burned-out was not backed up by extra copper, the minimum propagation zone (MPZ) length was small short, ~9 mm. Thus it appears that the cause of the failure is due to conductor motion. It also appears that any of the coil leads could have failed

After the M2 coil lead failure, the three-coil spectrometer set was trained to 270 A (~98 percent of design current). We did a series of tests that involved running the three-coil spectrometer set powered with the 300-A power supply to currents of 100 to 150 A, while powering coils E1 and E2 with the 60-A trim power supplies. This test showed that the field uniformity in the spectrometer good field region could be adjusted by currents from the two 60-A power supplies.

VI. THE THERMAL PERFORMANCE OF MAGNET 2B

The copper leads from room temperature to the HTS leads were not the only problem that occurred in magnet 2A. With no current in the new leads (leads 1b), the net heat flow to the top of the HTS leads would be higher than for the leads used in magnet 2A. This means that the temperature at the end of the copper plate farthest from the cooler would also be higher.

The AL-330 cooler changed the copper plate temperature distribution. When one subtracts the heat leak down the leads in the cases with magnet 2A and magnet 2B, one finds that the heat flow from the shield into the coolers was ~15 W lower for magnet 2B. In magnet 2B, we measured temperatures for all of the first-stage cold heads. Unlike magnet 2A, there was no heat being removed by boiling nitrogen in the tank attached to the shield. From the measured temperatures and temperature drops on magnet 2B, it was possible to estimate the thermal performance of magnets 1 and 2A [12].

The shield heat load was 80 to 100 W lower for magnet 1 than for magnets 2A or 2B [12], [14]. The reasons for part of this difference are not understood. The primary changes in the shields of magnet 2 were that magnet 2 has an added liquid nitrogen tank and two added vent lines. It is unlikely that these changes alone are responsible for the increased heat load onto the shield that was observed in magnet 2.

A key thing learned from magnets 2A and 2B is the importance of keeping the cooler first-stage temperatures less than 50 K. The ΔT between the tops of the HTS leads and the cooler cold heads is important. This is particularly true for the MICE coupling and focusing magnets. The distance between the leads and the coolers must be reduced. The copper plate must be made thicker and the heat from the copper leads must be spread evenly across the copper plate.

During the magnet 2B test, we measured the net heat flow into the 4 K cold mass. The most accurate measurements made were made using a positive displacement gas flow meter to measure net helium boil-off. The heat flow measurements appear to be simple, but the time constants for such measurements are long [10]. The apparent excess heat load at 4.3 K was from 1.05 W to 1.61 W. The net heat flow into the magnet appears to depend on the liquid level in the tank [12].

The apparent excessive heat leak into the spectrometer solenoid may be due to two factors: First, the heat flow into the cold mass can be greater than the 2nd-stage capacity of the coolers. Second, the connection between the coolers and the cold mass may not be very efficient. The free convection connection between the cooler second-stage and the helium tank was not simple as it was in the cooler tests [4], [10]. The liquid helium from the cooler second-stage condensers dripped into a horizontal manifold where the liquid spread out. The liquid was in direct contact with the boil-off gas from the magnet. This manifold increases the length of both the liquid and gas flow paths, which could be a contributing factor to reducing the efficiency of the cooler-to-magnet interface.

VII. Concluding Comments

The test of the MICE spectrometer solenoid was not what we had hoped for. We had expected the coils to train to their full design current while being cooled using with three pulse tube coolers and a single stage GM cooler. As expected, the single stage cooler greatly reduced the temperatures of the first stage cold heads by 30 to 35 K. The shield temperature was reduced by ~20 K. The reduction of the shield temperature did not reduce the heat load into the cold mass enough to permit the magnet to operate with the coolers alone.

The experiment demonstrated the importance of maintaining a low cooler first-stage temperature. The experiment also demonstrates the importance of reducing the temperature drop between the tops of the HTS leads and the cooler.

The cooler-lead experiment demonstrated the importance of have the correct conventional copper lead IL/A. Calculating the correct IL/A seems trivial, but part of the problem is not knowing what the residual resistivity ratio (RRR) of the copper cables that are part of the copper leads.

The location of the lead break in the M2 coil circuit is known. The break occurred in a single superconductor strand with very little copper (Cu to Nb-Ti ratio is 1.4). Since the strand passing through the feed-through was small in cross-section (1.32 mm^2 versus 2.97 mm^2 for the rest of the lead), it was more likely to move in a magnetic field. This strand was also more sensitive to conductor motion due to the lack of copper and an MPZ length of only 9 mm. The feed-through conductor will be backed up with added copper, which increases the feed-through conductor stiffness and the MPZ length within that conductor. The added conductor will ensure that the feed-through conductor is kept cold. It is clear that the cold mass helium tank must be kept full of helium.

The cooling of what may be the largest powered magnet cooled with small coolers is more of a challenge than we thought it would be. Additional two-stage coolers will be installed and we will reduce the heat loads into the cold mass and shield by as much as possible.

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